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PROCEEDINGS of ISMA 2019
International Symposium on Music Acoustics

13 - 17 September 2019 in Detmold, Germany

A parametric study of finger motions when playing the clavichord : towards characterization of expressive control.

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Abstract

The clavichord is considered to be the most demanding keyboard instrument in terms of finger control. This is because of its direct mechanisms: the key works as a lever. When the finger presses the key, the tangent (metal blade) on the key's extremity goes up and strike the string. And as long as the finger remains pressed on the key, the tangent remains in contact with the string, leading to string's tone variation. The loudness of the sound is proportional to the velocity of the key's displacement. Then there is a duality between loudness and pitch accuracy. This is the paradox of the clavichord. The objective of the study is to analyze experimentally the vibro-acoustical consequences of the instrument with respect to the gestural strategies of the finger. To proceed, an experimented player performs in different configurations two main gestures: the pushed and pulled gesture. A robotic finger is used to simulate different trajectories in terms of downward displacement and velocity. The study shows that the pushed and pulled gestures have opposed influences on the fundamental frequency and on the sound level. The robotic finger demonstrates that a rise in sound level without a rise in fundamental frequency is possible.

Keywords: Clavichord, gesture, robotic finger

1 INTRODUCTION

1.1 The clavichord's paradox

The clavichord is the earliest stringed keyboard instruments, dating back to the XVth century [1]. Its sound level is low compared to other stringed instruments, and it is the only keyboard instrument allowing for some pitch control. When a key is pressed, the corresponding pair of strings is impacted by a small metal blade (the tangent) placed at the end of the key. As long as the key is pressed, the tangent remains in contact with the strings. The tangent is at the same time the nut (i.e. one extremity) of the string and the string exciter (the string is then excited at a vibration node). It has been showed experimentally that the sound level of the clavichord is proportional to the tangent velocity at impact [7]. So the faster the key is pressed, the louder the sound becomes. However, when a key is pressed with a high velocity, the key's displacement tends to be higher. The tangent raises the string, then increases its tension, and thereby increases the vibration fundamental frequency. As a result, playing louder ends up in raising the pitch, if the key is pressed in a simple vertical motion. To control independently loudness and intonation would require a paradoxical gesture: at the tangent-string contact, the tangent should have enough velocity, but should not raise the string. In other words, the key should transfer all the tangent momentum to the string, but without raising it, or losing contact. This dependence between loudness and pitch accuracy is coined "the clavichord's paradox"[4, 5]. It is difficult, at least for human players, to achieve exactly such a motion. However compromises between tangent impact velocity and string displacement are possible.

1.2 Historical clavichord techniques

The clavichord is considered as the most demanding among keyboards instruments in terms of finger control. This is because every nuance of pressure of the finger on the key is likely to change loudness and intonation. In addition both finger velocity and displacement must be controlled because of the clavichord's paradox. To

Figure 1. Photo from above of the Hubert clavichord.

deal with these constraints, specific performance practice have been elaborated. Because of these constraints, the clavichord has always been highly praised as a pedagogical instrument. Several texts describing clavichord performance around Johann Sebastian Bach's circle, "Every Players first Grammatica" to quote J.G. Walther (1732) (see [12], page 169), mention a specific technique called "Schnellen" [11], which can be translated in French by "tire" [5] and in English by "pulled" (see for instance, J.J. Quantz, 1752, C.P.E. Bach 1752, Forkel 1802). In this technique, the finger tip is drawn back quickly after contact with the key, in a sliding motion.

1.3 Measurement and simulation of fingers motions

In a preceding work [4], the effect of vertical finger motion ("pushing motion") and sliding finger motion ("pulling") on loudness and pitch of clavichord tones have been studied. It has been shown that the pulling gesture is a better compromise for dealing with the clavichord's paradox: loudness and pitch are controlled more independently with pulled than with pushed motions. The aim of the present work is to study the clavichord's paradox with the help of new measurement techniques and robotic simulation: 1/ to measure accurately finger trajectories and their consequences on vibration and sound patterns (Section 2); 2/ to reproduce these trajectories using a robotic finger, in order to study the limits of the clavichord's paradox, and then the "optimal" trajectories, decoupling key velocity at impact and string displacement (Section 3).

2 MEASUREMENTS OF FINGER AND VIBRATORY MOTIONS

2.1 Experimental setup

The instrument under study has been built by C. d'Alessandro and C. Besnainou, and completed in 2007 (at The Paris Workshop, led by M. Ducornet, in Montreuil). It is based on a kit designed by E. Dancet and M. Ducornet after XVIIIth century unfretted clavichord models by G. Hubert. The instrument is not an exact copy of an historical model. It has been built especially for acoustic investigations, but it has occasionally been played in concert. The instrument has 51 keys, from C to d3, with double strings in brass. Its dimensions are 1267 mm x 358 mm x 112 mm. It is tuned at A=415 Hz, in a Kirnberger II temperament. Vibrating string lengths C = 1097mm, c = 926mm, c1 = 509mm, c2 = 262mm, c3 = 122mm.

The objective is to measure the vibration of the excited string resulting from the motion of the musician's finger. In preceding works, measurements were performed with the help of an accelerometer near the tangent, a string-tangent contact signal and a measurement microphone. It appeared necessary to measure directly the finger motion and the string motion, using non-invasive measurement devices. Finger motions are filmed by a high-speed camera (Phantom Miro M 120) with a 2000 frame per second rate. Several marks are placed on the finger. Trajectories of these marks are estimated thanks to image processing.

String vibrations are measured with the help of calibrated opto-switch sensors [8]. These sensors are optical forks, positioned around the string. The string motion in one direction is measured with accuracy and without contact. Only the vertical displacement of the string is considered here (although the horizontal displacement can also be significant). The string chosen for our measurements is the G2 string (length is 70 cm, fundamental frequency 185 Hz). The sensor is placed at 2 cm from the extremity of the string, near the bridge in order to be within its measurement range. Sound pressure is measured with the help of an omnidirectional DPA 4006-TL microphone placed at 30 cm above the soundboard. A set of 8 trajectories are recorded, using index and middle fingers, pulled and pushed motions for long and short notes.

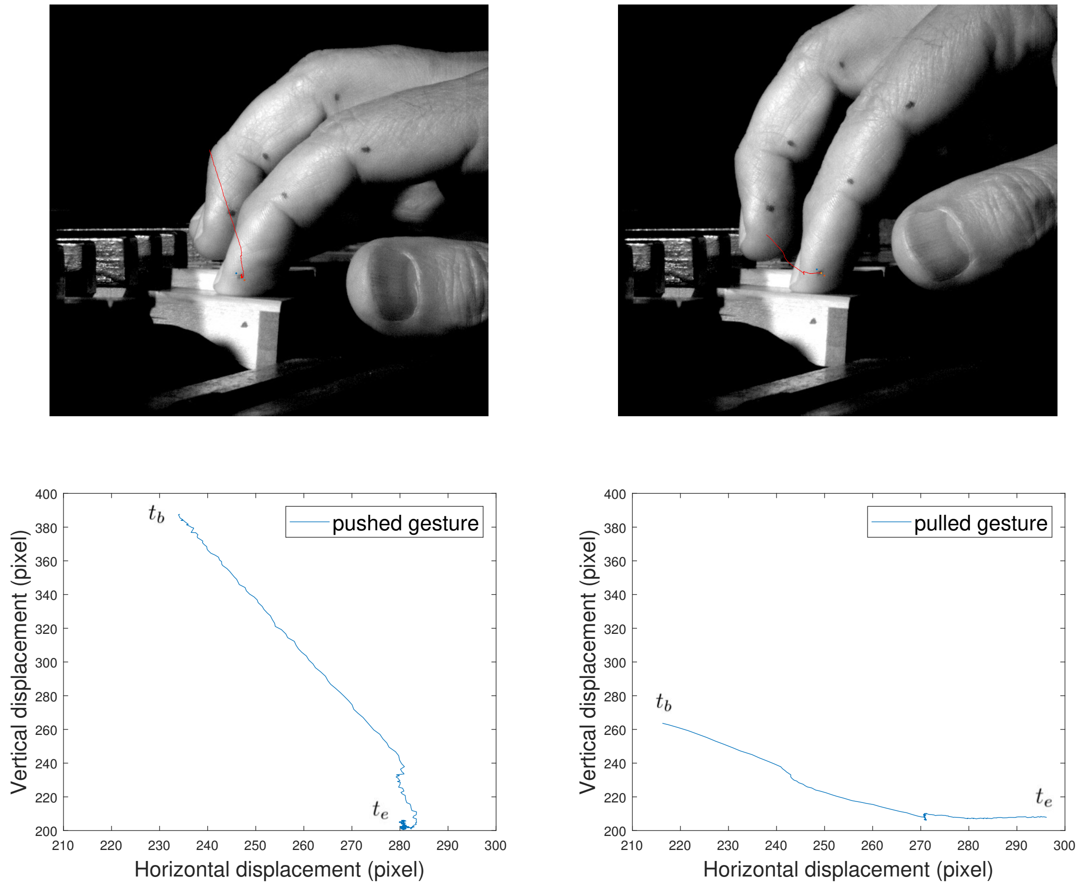

Figure 2. (Top) Images of the pushed (left-hand side) and the pulled gesture (right-hand side) performed by the index finger. (Bottom) Trajectories of the pushed (left-hand side) and the pulled gesture (right-hand side) performed by the index finger (with t_b the beginning time and t_e the ending time).

2.2 Results

In figure 2, we used the videos to extract the trajectories representative of the two distinct motions : the pushed and pulled gestures. The pushed motion refers to a vertical trajectory, the finger going mostly downward. The pulled motion corresponds to a vertical and horizontal trajectory, the finger sliding on the key and going downward at the same time. Figure 2 displays a selection of extracted trajectories. Note that the key depression is shallower in the second case.

Example of string vibration pattern are displayed in figure 3 and 4 for the pushed and pulled gestures by the index finger. As the sensor is placed near the bridge, the vibratory motion is of small amplitude, about 0.2 mm.

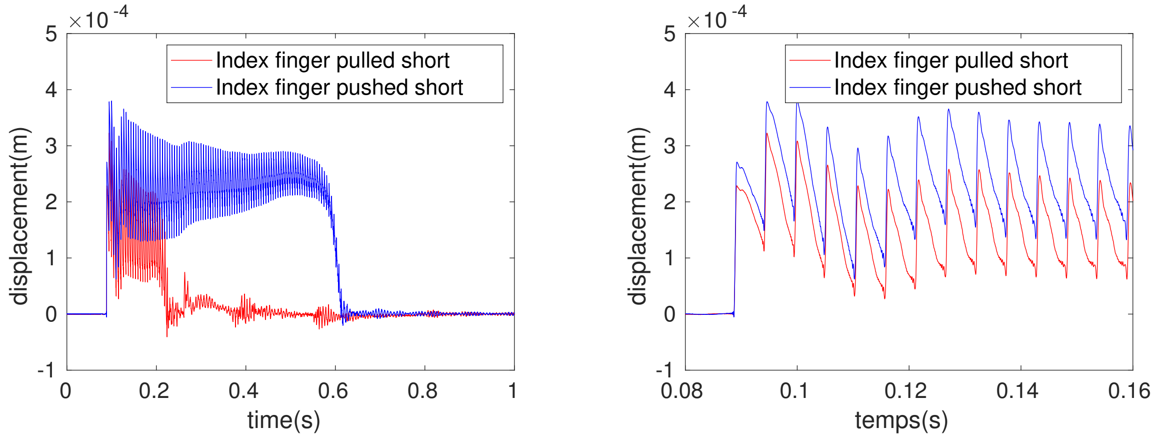

Figure 3. Vibratory signal of the G2 string excited by means of the two different trajectories done by the index finger with a short length (left-hand side), with a zoom at the beginning of the signals (right-hand side).

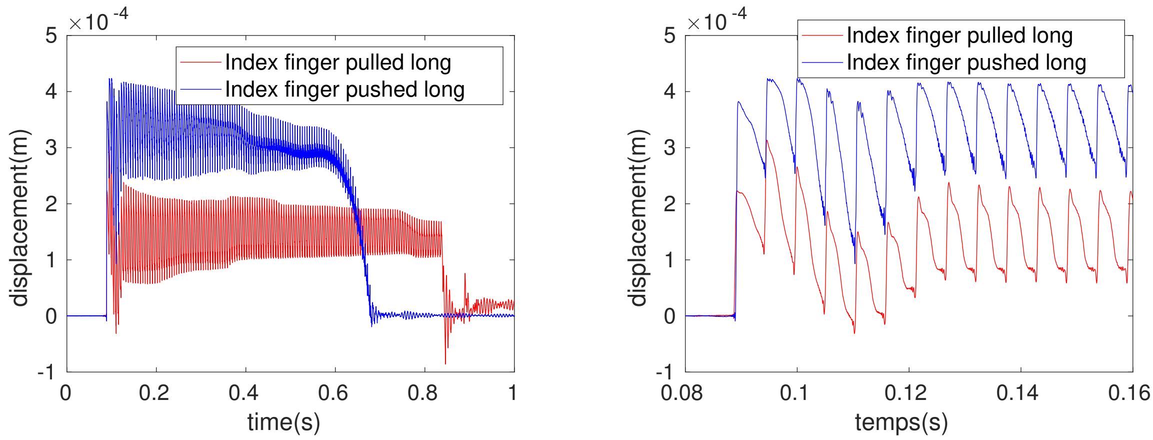

Figure 4. Vibratory signal of the G2 string excited by means of the two different trajectories done by the index finger with a long length (left-hand side), with a zoom at the beginning of the signals (right-hand side).

The string height is also small at this position, about 0.2-0.3 mm. It is much larger at the tangent position. The string is much more elevated in the case of the pushed gesture than the pulled one (see figure 3 and 4). Because of this difference in string height, the string tension and then the sound fundamental frequency is higher for the pulled motion. Note that the vibration amplitude is also larger in the case of the pushed gesture, resulting in a louder tone. Fundamental frequency is measured on the sound and vibration signals using the Yin algorithm [6] implemented in Matlab. Fundamental frequency with respect to time (G2 string) is displayed in figure 5. As predicted, the fundamental frequency is higher for the pushed gesture compared to the pulled gesture. The difference between the pushed and the pulled gesture is more than 4 cents for some conditions. Such a difference is perceptually noticeable. Fundamental frequency gives information about the way the musician deals with the contact between the tangent and the string with respect to time. In figure 5, one can observe that the fundamental frequency for the pushed gesture decreases with respect to time, whereas that of the pulled gesture remains around the same fundamental frequency although with some little hills. This shows that the key control differs for both gestures. These variations of finger depth after the string-tangent contact are certainly perceived in terms of quality of touch.

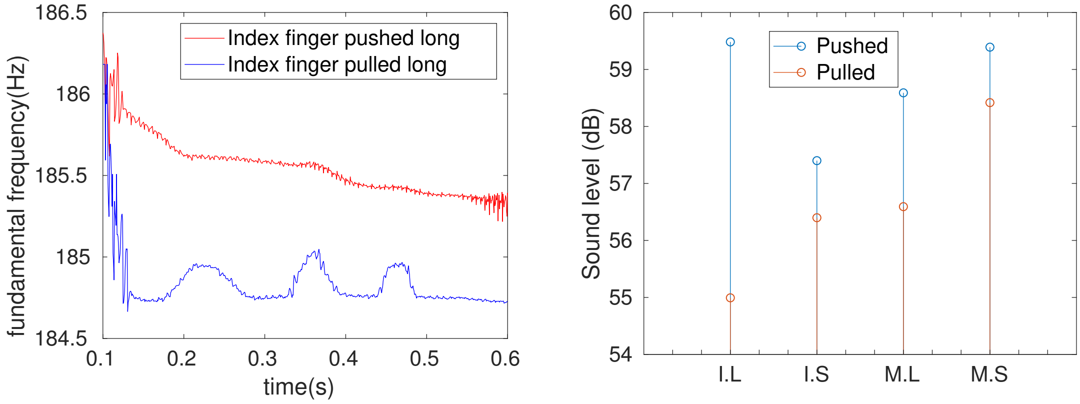

Figure 5. Fundamental frequency of the signals in the case of the pushed and pulled gesture done by the middle finger and the index finger (left-hand side). Sound level of the different exciting configurations (right-hand side) (I : Index finger, M : Middle finger, S : Short, L : Long).

Figure 6. Measurement devices: (left-hand side) optical forks for string displacement. (right-hand side) DRoPiCrobotic finger for key trajectory control.

The sound level in dB for the different microphone signals are displayed in figure 5 (integration time 250 ms). Pushed gestures produce higher sound levels than pulled gestures. This has already been observed on the signal amplitude in figure 3 and 4.

In summary, different gestures, corresponding to different finger trajectories, are producing different vibratory patterns of the string, and then different sounds. In the small set of recordings available, the pushed motions always produce a larger string displacement : the string is always raised higher, and the amplitude of vibration is larger. A larger amplitude of vibration results in a louder sound. A higher string height results in a higher fundamental frequency. For the same reasons, the finger motion in the case of pulled gestures gives lower fundamental frequencies and also weaker sounds. Note that in previous studies it has been shown that pulled motions, to some extent, allows for independent loudness and pitch control, a result that cannot be observed here, because no sample have similar loudness. These measurements are the first direct measurements of string height, and are in good agreement with the theory developed in [7].

3 ROBOTIC SIMULATION OF FINGERS MOTIONS

3.1 Experimental setup: the robotic finger

Measurements of finger motion show the dependence between string height, sound radiated and fundamental frequency. As predicted by the clavichord's paradox, it seems difficult to control simultaneously the key (then tangent, then string) velocity and displacement. The pulled motion provides a better control and a better management of the clavichord's paradox, because the finger trajectory is more complex: pressure on the string can be released after the tangent-string impact.

It is interesting to study the clavichord's paradox with the help of controlled and reproducible key trajectories. For this purpous, a robotic finger is used. The DROPIC robot [9] has been initially developed for simulation of finger trajectories in plucking gesture of harps [3, 2]. It has been applied to keyboard instruments in studies of the plectra effects for the harpsichord. [10]. The robotic finger has two degrees of freedom. It can reproduce any trajectory in a plane parallel to the axis of the key. Note that the key itself has only one degree of freedom. The effort for depressing a key is relatively weak, less than 2 N.

For a given starting trajectory, two parameters are considered and modified: downward displacement (resulting in string height) and its maximal velocity (corresponding to loudness). The A2 string (length is 59.1 cm, fundamental frequency 205Hz) is studied. The initial position of the robotic finger above the key is set before modifying either the velocity or the displacement. A joint measure of the string vibration by means of calibrated opto-switch sensors is performed. Three different velocities with the same displacement, and three different downward displacements with the same velocity have been programmed. The displacement of the key corresponding to a referent trajectory performed by the robotic finger is displayed in figure 8. The trajectory has a typical shape with a notch followed by a plateau. It is possible to adjust independently the depth of the notch and the height of the plateau, that correspond roughly to the key velocity at contact and to the string height.

3.2 Trajectories simulation and sound results

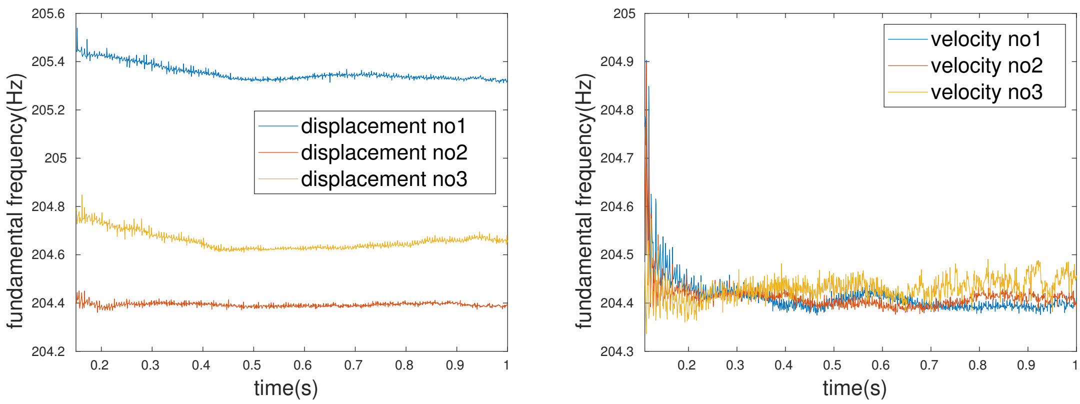

Figure 7. Tracking of the fundamental frequencies of the signals in the case where we modify the displacement of the key (left-hand side) and in the case where we modify its velocity (right-hand side).

Systematic variations of displacement and velocity are performed. Note that in this second experiment, the note studied is A2 instead of G2 studied in Section 2. These two notes are close enough to be compared. In figure 8, the key velocity is varying but the key depth is constant. The key depth is about 5-6 mm in this case. The resulting average string elevation is 0.1 mm.

Figure 7 displays the fundamental frequency of the different signals measured when the key is played with

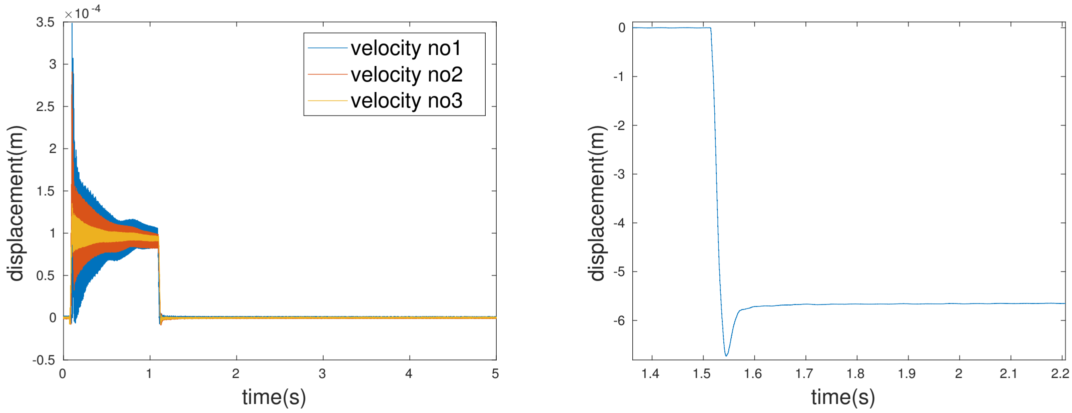

Figure 8. Temporal signals of the A2 string produced by the different velocities of the key (left-hand side). Displacement of the key in the case of the referent trajectory performed by the robotic finger (right-hand side).

the robotic finger. The resulting fundamental frequency does not change, while the amplitude of the signal increases. This shows that the trajectory of the finger is well repeated by the robot no matter the change in velocity. Moreover, it demonstrates that the clavichord's paradox can be managed with appropriate trajectories. These results also confirm that the displacement of the key is directly linked to the string's fundamental frequency. Conversely, changing the displacement of the key but maintaining the same velocity produces changes in fundamental frequency. However, fundamental frequency is very stable in the case of the robotic finger compared to a musician's finger (compare figures 7 and 5).

These results demonstrate that a robotic control is able to manage the clavichord's paradox. Whether human and robotic control are comparable is questionable. In the present experiment, the robotic finger has no haptic or sound feedback: the trajectories are optimized directly, without any perceptual loop. On the contrary, human control relies much on audio and haptic feedback. The musicians tend to control the contact between the tangent and the string after the excitation by modifying the key position according to the perceived effect of their initial motion. This variation in time of the key position is probably an essential feature of the specific style of a musical performance. Another difference between the robotic finger and human finger is their mechanical and dynamical properties. Human fingers have a much limited range of velocity and acceleration than the robot. Oscillations of the key-string-finger system that are observed in human control [7] seem negligible in the case of the robotic finger (see the displacement of the key in figure 8).

4 CONCLUSIONS

This work presents two experiments addressing the clavichord's paradox, i.e. simultaneous control of velocity and displacement of the string and tangent when playing the instrument. In a first part, new measurements using a new methodology is used. Two types of finger trajectories have been used for performing two different motions : the pushed and the pulled gesture. This experiment confirms the dependence of displacement and velocity, and the possibility to modulate this dependence with appropriate gestures. In the second experiment, a robotic finger is used to further optimize the key trajectory, by modifying in terms of velocity and downward displacement a referent trajectory. In this case it seems possible to manage the clavichord's paradox, and to control independently velocity and displacement, i.e. intonation and loudness of the instrument. Whether a musician would be able to effectively perform this type of movement remains an open question.

ACKNOWLEDGEMENTS

The authors thank Sebastien Guy and Laurent Quartier for their help during the measurements.

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